CHAPTER 1

General introduction
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Healthy aging refers to maintaining physical and cognitive health, avoiding disease and disability, and remaining active and independent. Unfortunately, not all of the 3 million adults aged 65 and over in The Netherlands (17% of the total population) enjoy healthy aging [1,2]. Natural aging is associated with a decline in physical function and cognition and has serious consequences for mobility, fall risk, quality of life, health care dependence, and mortality [3,4]. The aging population is a growing concern for today’s society. The high cost of fall-related injuries and long-term care for the elderly present a tremendous social and financial burden for family members [5]. Maintaining independence, autonomy, and quality of life as long as possible is of utmost importance for old adults, their families, and caregivers. Under the guise of ‘prevention is better than curing’ a variety of prevention methods aims to improve or maintain physical and cognitive function in old adults.

Prevention strategies can be divided into two approaches: 1) prevention by real-time monitoring of individuals to detect high-risk situations and provide signals for immediate care, and 2) prevention through prolonged intervention, such as exercise training, medication review, and educational programs [6]. Before implementing appropriate prevention methods for individuals, one must accurately determine whether there is a high risk for a fall or mobility loss. Emerging technological solutions may lead to more effective and tailored prevention based on the ability to detect small but essential changes prior to an overt manifestation of mobility impairment such as a fall or inability to walk.

The present thesis addressed two different, yet conceptually interlinked, prevention issues. The concept that links the two thesis parts is prevention. One aim was to identify situations that can lead to falls in highly vulnerable psychogeriatric patients. The second aim was to detect signs of deterioration in gait and dynamic balance in still healthy old adults who might fall later in life. Thus, part one describes the search for and development of a fall prevention sensor system in a long-term care facility. The target population for this first project was frail elderly persons with dementia who were at high risk for falling. These patients lived in a psychogeriatric ward of a long-term care facility. In this vulnerable group, falls occur frequently and are associated with substantial physical, psychological and financial consequences. The aim of this project was to assess the circumstances of falls and evaluate the possibility of monitoring residents with a sensor-based system to detect high fall risk situations and provide feedback to the health care staff for immediate care. The project took into account the experiences, attitudes, and expectations of health care staff (end-users) toward a fall prevention sensor system during system development. The second part of this thesis originates from the request of clinical practitioners and geriatric departments to develop a small, low-cost, user-friendly, and accurate device to detect early markers of decline in balance and gait instability, so as to enable timely and targeted interventions to slow or even stop the decline process. Considering the tremendous mobile technology advances and the increased number of smart device users, we investigated the
validity and reliability of the built-in, tri-axial accelerometer in the iPod Touch to record gait and balance capacity. Furthermore, the relationship between gait variables derived from the accelerometer signal and age was examined to provide a frame of reference for gait pattern changes due to natural aging.

Technology-based fall risk assessment in long-term care residents with dementia

Falls in long-term care facilities

In The Netherlands, 165,000 adults older than 65 live in long-term care facilities [2]. People living in long-term care facilities are most often diagnosed with cognitive impairment or severe physical limitations. Although the health problems in this population vary widely, these people have in common that they can no longer live independently. Long-term care facilities face the challenge of providing care and facilitating a safe and comfortable stay, while maintaining optimal autonomy and quality of life. Unfortunately, a fall can ruin previously stable health instantaneously. Cognitive problems in combination with physical limitations of long-term care residents increase fall risk. Consequently (and unfortunately), falls occur frequently in long-term care facilities. These falls lead to physical consequences (e.g., injuries, open wounds, fractures, and brain damage) and psychosocial consequences (e.g., loss of confidence, anxiety, and depression) [7–9]. After a fall, old adults become more dependent, with an ensuing reduction in quality of life. Every year 7,700 long-term care residents aged 65 years or older visit a hospital emergency department in The Netherlands after an accident, 95% of which are due to falls [9]. On average, the health care-related costs are €13,000 per accident, a significant financial burden compared with the average annual per capita costs of €8,400 for the total population of old adults aged 65 years and over. Almost half of residents experiencing an accident require hospitalization, of whom 60% experienced a hip fracture. Additionally, 510 residents die each year as a result of accidents in long-term care facilities. Although those numbers are alarming, these costs most likely underestimate the real costs of fall-related injuries in long-term care residents because these numbers only include accidents registered in Dutch hospital emergency departments [9]. To reduce the number of falls and fall-related injuries in long-term care residents with dementia, effective fall prevention is necessary.

Fall prevention in long-term care facilities

There are multiple fall prevention programs specifically developed for long-term care residents. These interventions include: balance and mobility training, behavior-changing interventions, vitamin D and calcium supplementation, and programs combining multiple intervention methods [10–12]. Unfortunately, only a few fall prevention programs have been successful. The recipe for a successful fall prevention program seems to be a multifaceted program consisting of resident-specific strategies (e.g., medication review,
risk assessment), group-specific strategies (e.g., exercise sessions) and general intervention strategies (e.g., staff education, environmental modifications) [12]. However, these fall prevention programs are rarely implemented in institutions because such programs are labor- and time-intensive for health care staff [13,14]. Additionally, the cognitive tasks of learning fall strategies, balance and mobility training, or recognizing and avoiding high fall risk situations are difficult for residents with dementia. Because prevention through intervention has had limited success for long-term care residents, prevention by individual monitoring seems to be a suitable alternative. Although health care staff cannot continually monitor residents, technology-based solutions can be used to assist in monitoring residents and detecting adverse events, including falls. Fall detection devices are available, including accelerometers detecting falls based on the magnitude of acceleration signals or camera systems identifying someone lying still on the ground for several minutes [15–17]. However, to avoid fall consequences, a high fall risk situation needs to be detected prior to the fall occurrence. Because more than 50% of all falls occur in residents’ bedrooms [8], bed sensors have been introduced. The alarm systems, using infrared or pressure sensors, notify the health care staff when a resident is getting out of bed and assistance is needed [18–23]. However, bed alarm systems are freedom-restricting, and circumstances and locations of falls are not fixed. Falls occur due to a wide range of circumstances (e.g., restlessness, medication, cognitive status) that produce dynamic risk factors that change over time and differ between persons [24–26]. Therefore, monitoring is required of multiple events and locations with individual risk detection. Recent developments in technology, including sensor miniaturization, multiple sensor use, data transmission, and data processing make it possible to continually monitor movement, human physiology, and behavior for longer periods. Data processing enables early and accurate detection of abnormalities in behavior or movements, as well as identification of circumstances immediately preceding falls for individual residents. Personalized fall risk decision-making models can be developed to recognize situations and events that increase fall risk. The decision-making models can learn over time based on accumulated data and can adapt to changes in resident status.

The INTERREG IV A ‘Telemedicine & Personalized Care – project fall prevention’ aimed to develop a smart fall prevention sensor system that automatically identifies increased fall risk in long-term care residents with dementia. After detection of a high fall risk situation, the system is designed to rapidly alert health care staff. This alert enables tailored care and increases the effectiveness and quality of health care. Because this project requires expertise in various disciplines, a multidisciplinary collaboration between companies integrating technology and processing large datasets, clinical settings, and knowledge institutions was initiated.
Sensors for fall prevention

The first step in developing a reliable and accurate system is to evaluate the current state of prevention technologies and to determine the conditions for a successful fall prevention technology. There is a broad range of sensors available to detect specific events (such as standing up from a chair or leaving a certain room) and alert the health care staff. Event detection can be based on cameras, infrared sensors, inertial sensors, global positioning system (GPS) or pressure sensors [27–30]. The sensors can be divided into two main categories: wearable and non-wearable sensors. Wearable sensors can be placed in shoes, clothes, around the wrist in a bracelet, or hanging as a necklace; therefore, they have the advantage of not being fixed to one specific location. However, the problem with wearable sensors is that residents with cognitive impairment suffering from confusion or physical inconveniences may simply remove shoes, clothes, or a bracelet [22,31] This removal results in inaccurate monitoring or absence of monitoring.

Non-wearable sensors seem to be a good alternative for long-term care residents with dementia. In the Ambient Assisted Living (AAL) project, the surveillance system ‘Rosetta,’ was developed to monitor old adults with dementia living independently [32,33]. A sensor system based on cameras, infrared movement detectors, a bed mat, smoke alarms, and magnetic door sensors recorded the lifestyle of community-dwelling old adults with dementia. The data recorded in the first two weeks were used to define the normal daily routine. Afterwards, deviations from the normal daily routine such as wandering during the night, changing eating and drinking patterns, and bathroom use could be identified. Unfortunately, this monitoring system is not suitable for fall prevention in intramural care facilities because it cannot deal with multiple persons in one room and because it detects fall incidents instead of predicting them. Nevertheless, owing to delays in, and in some cases avoidance of, institutionalization of the participating old adults, this project demonstrates the high potential of non-wearable sensors in combination with a decision-making model to use as a monitoring system.

Fall risk factors

The development of an effective fall prevention system with a decision-making model requires information concerning factors that lead to falls. Factors contributing to falls in long-term care residents with dementia include: cognitive impairment, fall history, incontinence, polypharmacy, use of antidepressants and benzodiazepines, gait disturbances, behavior problems, functional dependence, anxiety, poor attention and orientation, urinary infection, slippery floors, and poor lighting [34–39]. Although we know that when more fall risk factors are simultaneously present fall risk increases, the relationship between risk factors and the association with fall incidents is still unknown. Complex interactions among fall risk factors underlie many falls [40]. Some factors may reinforce each other, whereas other factors may have counteracting effects. Understanding the relationship between risk factors and the association with falls could contribute to an accurate fall risk
decision-making model. Monitoring residents and measuring multiple factors known to be involved in falls may enable health care staff to intervene and reduce fall potential.

It is unlikely that a standard fall risk decision-making model will fit for all long-term care residents with dementia. Long-term care residents with dementia represent a heterogeneous patient group. These patients experience a range of cognitive dysfunction combined with diverse co-morbidities, frailty markers, and medication use. Each resident would have a unique combination of factors predisposing to falls. Therefore, a personalized fall risk decision-making model is needed. Moreover, physical and cognitive function may change rapidly in long-term care residents. For example, a resident who is independent one day can become wheelchair-dependent within weeks. Such changes require a dynamic fall risk decision-making model that can adapt to ever-changing individual patient living and medical conditions.

**User involvement**

Introducing technology in health care institutions significantly impacts the work of health care staff and changes daily routines. A large number of projects has failed to introduce technology into clinical practice, not due to flawed technology, but rather due to the lack of involvement of health care staff (end-users) throughout the technology development and implementation. Consequently, technology developed without user involvement remains unused. The user-as-designer approach includes user involvement early and continuously during the design process [41]. The user is a part of the development team that finds solutions to address the needs and values of the health care staff and their patients. The user is the expert concerning the requirements and demands from the clinical practice, whereas the technicians and data analysts know the opportunities and the possibilities of technology use. User involvement promotes a sense of empowerment and contributes to more efficient and effective solutions that may work better than solutions conceived without stakeholder input. Successful development and implementation can increase ease of use and learning, adoption, and satisfaction of users.

**Objectives**

The final goal of the INTERREG IV A project was the development and implementation of a smart fall prevention sensor system using wireless integrated video and bed mats (pressure sensors) to continuously monitor resident movements and physical status in his living surroundings. At the same time, biomarkers, such as heart rate, body temperature, and blood sugar levels, as well as chart data on behavioral and medical status are monitored and combined with the sensor data. All available information is then integrated and interpreted in an effort to generate a multivariate data analysis-based personal, decision-making model. The result is a dynamic system that can learn over time and adapt the decision models according to the events and other changes.
The first steps to develop this technological solution for fall prevention in long-term care residents with dementia are described in the present thesis. The first three objectives were to:

1) review the effectiveness of fall prevention technologies used in intramural care facilities with respect to fall rate and fall-related injuries, false alarms, and user experience;
2) determine fall rate, fall-related injuries, and circumstances of these falls in long-term care residents with dementia. Additionally, the relationship between patient characteristics (classified into seven domains: demographics, activities of daily living (ADL) performance, mobility, cognition and behavior, vision and hearing, medical conditions, and medication use) and fall rate was examined;
3) assess the attitude of caregivers toward fall prevention, fall prevention technology, and policy making.

**Technology-based gait assessment in healthy adults**

**Changes due to aging**
Natural aging is characterized by skin wrinkles, gray hair or baldness, slowness, rigidity, sarcopenia, vision and hearing impairments, and forgetfulness. Though the visible changes due to aging may appear late in adulthood, the onset of the aging process starts in early adolescence. The progressive deterioration of muscle mass and muscle function starts around the age of 30 [3]. Until the age of 50, there is moderate decline of muscle mass of about 10%. After the age of 50 the decline accelerates, leading to an annual decrease of up to 2% [42]. Additionally, cognitive processes change while aging, whereby reaction time increases by 25% between ages 20 and 60 [3]. Natural aging is inescapable; strength, range of motion, cognition, reaction time, proprioception, and the sensory motor system will deteriorate over the years and will more or less influence mobility, learning capacities, functional abilities, activities of daily living, and quality of life [42,3,43].

As a consequence of natural aging, postural control and gait will change as persons grow older. However, gait changes can also occur as a result of age-related neurologic and non-neurologic disorders [44–47]. In fact, immobility, frailty, falls, dementia, institutionalization, and even early death in old adults have been associated with early detected gait abnormalities [48–51]. Identifying gait abnormalities at an early stage and monitoring gait changes over time might enable timely identification of abnormal decline and offer the opportunity for early and personalized interventions to reverse or slow the progression of balance and mobility impairments and disease evolution.

**Gait and balance assessment**
Gait speed is the most commonly used gait parameter to discriminate old adults with certain pathologies from their healthy peers. Gait speed is reduced in Parkinson’s disease,
multiple sclerosis, dementia, frail old adults, and fallers [44,46,52–55]. Although decreased gait speed can be considered as deviation from natural aging, this parameter is not specific and therefore not appropriate to detect early changes in gait quality. Additionally, tests especially developed to assess gait and balance ability often use a threshold to categorize individuals (e.g., “at risk” or “not at risk”). For example, the Timed Up and Go (TUG) is an easy and quick test to perform; however, there is growing evidence indicating the limited predictive value of the stated threshold to distinguish fallers from non-fallers [56]. Additionally, many functional tests suffer from ceiling effects and do not address changes due to balance and mobility [56,57]. Therefore, a sensitive and more specific gait assessment test is necessary, including a reference frame of gait changes occurring during natural aging, to identify old adults as soon as gait abnormalities emerge.

**Sensor devices for gait assessment**

Currently, various sensors are available to quantitatively and objectively assess gait and postural ability. These devices range from laboratory-bound sensors (e.g., Optotrak and Vicon motion analysis systems and force plates) to small wearable inertial measurement units (IMUs) with embedded gyroscopes, accelerometers, and magnetometers to be used outside the laboratory. For scientific purposes, both laboratory-bound sensors and IMUs are frequently used to determine gait and balance abilities [6,58–60]. However, an assessment device for clinical settings would preferably be small, lightweight, easy to transport and inexpensive. The tri-axial, stand-alone accelerometer, fixed to the trunk at the 3rd lumbar vertebrae, has proven suitable to objectively collect gait data. Additionally, these stand-alone accelerometers have demonstrated reliability and accuracy [61–64]. They have been used for years to quantify gait and offer a large range of movement-describing features. Various time, amplitude, and frequency variables can be computed from trunk acceleration signals in three dimensions. Based on peaks in anterior-posterior (AP) acceleration signals, the foot contacts can be detected [65,66]. From the foot contacts, step and stride variables can be determined, including stride time, stride variability, and step symmetry [67]. Additionally, the root mean squares (RMS) of the acceleration signal provide information about gait variability [67]. Gait smoothness is determined from content signal frequency [68]. Furthermore, gait variables derived from the signal trajectory, such as the sample entropy and maximal Lyapunov exponent, provide insights into the predictability and local stability of gait [69–71].

Numerous studies have demonstrated that data derived from trunk accelerometers can differentiate between gait of young and old healthy adults, fallers and non-fallers, and patient populations and healthy controls [44,50,72]. Old adults seem to walk with less symmetry, more variability, and less stability compared to healthy young adults [73]. Additionally, various gait variables are associated with fall risk, Parkinson’s disease, multiple sclerosis, and dementia [44,47,50,74]. These variables include gait speed, stride time, and different variability and stability-related measures (e.g., local dynamic stability,
smoothness, and predictability of gait pattern). Stand-alone accelerometers introduced into clinical practice would facilitate objective and accurate gait assessments to provide a variety of information about gait ability. Despite their advantages over other objective measures, stand-alone accelerometers are still confined primarily to use in the research setting. The need for specialized staff to perform measurements, analyze data, compute variables, and correctly interpret results limits widespread clinical use of stand-alone accelerometers. Clinical practitioners need and want objective devices that measure gait ability easily, accurately, and in a user-friendly way.

**Smart devices as gait assessment instruments**
The recent rapid development of smart phones, iPods, and similar smart devices provides an interesting alternative to assess gait and balance, as they are equipped with build-in, tri-axial accelerometers. Smart devices are relatively cheap, easy to use and many people already possess smart devices. Smart devices have the capacity to collect and store data, which can be conveyed wirelessly to a remote location for data processing. Additionally, data can be sent to other smart devices or a personal computer to provide direct access for clinicians or caregivers without the need for complex software or a patient visit. Applications are being developed to record and store balance and gait task data. These applications might be extended with algorithms that provide feedback to users or clinicians about gait ability.

**Objectives**
Smart devices seem to have the capacity to accurately and consistently record balance and gait data [75–77]. Nishiguchi et al. (2012) showed that an android-based smartphone can collect reliable and valid gait data in healthy young adults [77]. In addition, Patterson et al. (2014) evaluated software developed to access the iPod and iPhone accelerometer output and translated such data into balance measures. The results of their pilot study indicated that accelerometers provided consistent balance scoring for healthy young adults [75]. However, validity and test–retest reliability might be different for different task conditions or different age groups. Furthermore, a frame of reference for gait changes due to normal aging is still lacking. Therefore, the fourth and fifth objectives of this thesis were to:

4. assess the validity and reliability of the embedded accelerometer in the iPod Touch during gait and postural tasks under different conditions (eyes open, eyes closed, concurrent cognitive dual task) in participants over different ages;

5. determine the relationship between gait variables and age in healthy adults between 18 and 75 years old, and to examine the ability of the gait parameters to discriminate between healthy young and old adults.
Outline of this thesis

In the first part of this thesis, the first steps in the realization of a smart fall prevention sensor system to identify long-term care residents with dementia are described. Chapter 2 provides a synthesis of the effectiveness of fall prevention technologies used in intramural care facilities with respect to fall rate, fall-related injuries, false alarms, and user experience. Chapter 3 describes the fall rate, fall-related injuries, and circumstances of falls with respect to time, location, and whether or not a fall was witnessed by the staff in a long-term care facility with residents with dementia. Additionally, the relationship between patient characteristics (classified into seven domains: demographics, ADL performance, mobility, cognition and behavior, vision and hearing, medical conditions, and medication use), and fall rate in these long-term care residents with dementia are presented. Chapter 4 gives an overview of the user requirements of the staff of a long-term care facility for a fall prevention system based on smart technology. This chapter presents what was learned about user experiences with the currently used sensor systems, as well as the specific requirements and expected effects of a new fall prevention system.

The second part of this thesis addresses whether and how the iPod Touch is an appropriate instrument to measure gait ability in young and old healthy adults. Chapter 5 focuses on the validity and reliability of the embedded accelerometer in an iPod Touch during gait and postural tasks under different conditions in participants over different ages. Young, middle-aged, and old adults performed walking and standing tasks under different conditions (e.g., eyes open, eyes closed, concurrent cognitive dual task) while wearing a stand-alone accelerometer and the iPod Touch. Chapter 6 pursues a frame of reference for gait changes due to natural aging. Because the inter-relationship between the various gait variables used to characterize gait is unknown, a model is built to investigate the relationship between the gait variables and age. The identified gait variables sensitive to change over age are presented and their ability to distinguish younger adults (ages 18 to 45) from older adults (ages 46 to 75) is described. Finally, the main results of the thesis are summarized, and recommendations and directions for future research and clinical practice are discussed in Chapter 7.
References


